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SOIL AGGREGATE FORMATION

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Aggregates are the structural elements of soil. They have been formed by the cohesion of smaller mechanical fractions such as clay, silt, and sand. They consist of an intimate grouping of a number of soil grains into clusters. The process by which these aggregates are formed is one of the most important phases of soil structure.

In much of the previous thinking, the soil-aggregation process has been confused with that of flocculation. Flocculation and stable-aggregate formation are not synonymous. The former is primarily electrokinetic in nature. Primary particles with a high electrokinetic potential repel each other in a suspension. When the potential is lowered sufficiently, a collision between particles results in a mutual attraction and the formation of a floccule. The floccule is stable only as long as the flocculating agent is present. Flocculation is the condition by which the mechanism of aggregate formation can function. The process of flocculation is generally pictured as the separation of a dispersed phase, in the form of flocs, from a dispersion medium.

In water-stable aggregates the grains are so firmly held together that they do not readily disperse in water. In other words, aggregate formation requires a cementation or binding together of particles. Flocculation may aid in the aggregation process, but is not the aggregation process itself.

CALCIUM AND SOIL AGGREGATION

It is almost universally recognized that lime improves the physical properties of the soil. Moreover, it has been demonstrated quite conclusively that the poor structure of alkali soils can be improved by replacing the sodium with calcium. These facts, along with the laboratory observations that clay suspensions can be flocculated by calcium salts, have led to the widely accepted viewpoint that the beneficial effects of lime are due to its ability to flocculate the soil colloids.

There is little doubt that the effect of calcium on the reclamation of alkali soils is primarily associated with the more favorable influences of the calcium ion on the properties of the soil colloids, as compared with the effect of the sodium ion. Sufficient evidence is available to show that Na-saturated soils are more highly hydrated and dispersed than Ca-saturated soils (8).[1]

A different situation exists when the effects of calcium on the aggregation of acid soils are thoroughly analyzed. It has been generally accepted that the flocculating effect of the calcium is a contributing factor in stable granulation. Recent experimental observations, however, indicate that the direct effect of the calcium ion on the aggregation of acid soils is not as important as was originally considered. Liming under field conditions produced little or no structural improvement unless used in connection with a management system that maintains a good supply of biologically active organic matter (3).

These observations call attention to the fact that flocculation is not the same as granulation. In order to have stable granulation there must be a cementation of the flocculated particles. A possible "linking" action of Ca in the binding of clay and polyuronides to form good water-stable cements was advanced (65). Some investigators believe, however, that the chief effect of calcium upon aggregate formation may be indi-

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[1] Numbers in parenthesis refer to Literature Cited, p. 16.

rect, that is, it affects the nature of the organic matter produced.

TYPES OF CEMENTATION IN SOILS

Most of the cementing agents in soils were thought at one time to be irreversible or slowly reversible inorganic and organic colloids. Accordingly it was assumed that sands and silts could not form crumbs or aggregates (83). More recent investigations have shown this latter assumption incorrect (64). Four distinct agents have been suggested as functioning in crumb formation through cementation of soil particles. They are clay, iron hydroxide, organic matter, and substances produced by soil microorganisms. An organic-inorganic linkage of Ca and polyuronides with clay fractions has also been suggested (65).

CLAY AND SOIL AGGREGATION

Under many conditions clay functions directly as a binding agent in the formation of soil aggregates. Baver (8) found that the smaller clay particles are usually more effective in the formation of aggregates than the larger ones, and Boller and Stephenson (9) found that clay is more active in forming small aggregates than large ones. The aggregation of Gila clay was a function of the 2-micron soil fractions (34). A certain percentage of clay to coarse particles was essential to the formation of aggregates in sandy loam soils (55).

Aggregation was pronounced on two clay soils which were alike in that their clay mineral was montmorillonite but were different in their calcium and organic-matter content (86). A number of nonlateritic soils had good correlation between the amount of aggregation and their clay content when the organic-matter content was low, and between the amount of aggregation and the organic-carbon content where the clay content was low (9). However, there was little significant correlation in these soils between the amount of aggregation and one of these factors if the other was high. The effect of clay as a binding agent generally increases as the organic-matter content of the soil declines (8), and decreases as the organic-matter content increases (13). Clay and organic matter were about equally significant in aggregate formation.

Clay and dispersible organic matter in mixture was better than clay alone for cementing fine sand. However, the aggregation produced by the mixture was less than the total amount of aggregation produced in the sand when clay and organic matter were used separately (15, 16).

While clay and organic matter can interact to form a new complex if they are both free from exchangeable bases, there is no evidence that this new complex plays any special role in aggregate formation (55).

Russell (70, 71) suggested that aggregate formation is dependent upon an interaction between the exchangeable cations on the clay particle and the dispersion of liquid. His investigations indicate that the formation of aggregates is limited to particles smaller than 1 μ in diameter, is a property of only those clays having a relatively high base-exchange capacity and is brought about only by those liquids, the molecules of which have an appreciable dipole moment.

Russell was of the opinion that clay particles are not spherical but plate- or disk-shaped, that they are broader than they are thick, and that they adhere more strongly to one another if they are suitably orientated with respect to one another, probably adhering better if the disks lie parallel, piling upon each other rather than forming large thin plates. This is the arrangement expected in his link hypothesis if, as is probable, the exchangeable ions are either uniformly distributed over the whole surface or reside mainly on the two flat surfaces of each disk.

The belief was expressed that water-stable aggregates form only in the presence of a dipole liquid and that for maximum aggregation solvation of the exchangeable ions of the clay complex also is necessary (53).

This theory can be extended to explain qualitatively certain experimental results (32, 33). By using a single soil there was an inverse relation between the hardness of the crumb and its water-stability as the exchangeable ion and some other conditions were varied, provided the mechanical mixing of the paste before drying was done in the same way (32). If, as already suggested, water instability is typically caused by a high proportion of the exchangeable ions dissociating from the clay surface, this inverse relation would follow as a natural consequence, for the greater the dissociation of the exchangeable ions the greater the number of links that can be formed. Thus the harder the crumbs on the one hand, the greater their water-instability on the other.

This hypothesis also explains why crumbs, such as those of a sodium soil, may be unstable in water but stable in a salt solution of suitable concentration. For if water-instability of crumbs is caused by the larger resultant negative charges built up on adjoining clay particles

by a proportion of the exchangeable ions dissociating and moving away from the immediate vicinity of the surface, this action will be decreased by the presence of an electrolyte. The electrolyte in this case lowers the electrokinetic potential on the clay surface, which causes the exchangeable cations to remain closer to the clay surface. This reduces the resultant positive charge on adjoining clay particles, and thus increases the force of repulsion between them.

Russell's orientated dipole-cation-orientated dipole theory requires moisture for the formation of water-stable aggregates. A straight line relationship for decreasing moisture content and increasing aggregate stability was obtained for clay-sand mixtures (58). Four soils, with moderate clay and organic-matter content gave curves with a maximum aggregate stability near the moisture equivalent. Similar results were obtained from the addition of ground alfalfa to montmorillonitic clay-sand mixtures. Aggregate stability decreased with moisture content both above and below this value.

Russell recognized factors other than moisture content. In commenting on the findings of Geltzer (21) he was tempted to suggest that the structure-producing capacity of decomposing organic matter was due to a sticky substance produced during the decomposition of the organic matter.

The drawing together of the colloidal particles, which occurs during the formation of the phases of the aggregate state, leads to a deformation of the ion envelope around these colloidal particles (75). This deformation is expressed in a compression of the ion layer or in a decrease of the distance of the electric double layer, and must affect all the properties depending on the dimension of the electric double layer.

The former conception that the particles forming the soil aggregate are held together by the tension of the water film is supplemented by the finding that surface film creates a definite orientation of the particles in relation to one another. The tenacity of the bond between the separate parts of the soil structural aggregate lies in the stability of the group arrangement of the particles. The most stable arrangement of particles is the homogeneous one (75).

IRON HYDROXIDE AND SOIL AGGREGATION

Iron hydroxide, or probably iron hydroxide combined with some

form of organic matter, can cement soil particles together. In extreme cases, often seen in B-horizons of some soil profiles, the bonding has progressed so far that the particles form hard concretions devoid of pore space and requiring drastic treatment to be redispersed into their component particles. But in the initial stages of cementation, aggregates are produced which have a more normal pore space and can be readily redispersed. The iron hydroxide is then simply acting as a weak cement which becomes stabilized upon drying.

Free iron was thought to have been an important factor influencing the granulation of lateritic and semilateritic soils (44). The free iron probably served a dual purpose, the part in solution functioning as a flocculating agent and the other as a cement.

EFFECT OF ORGANIC MATTER ON AGGREGATION

It is generally recognized that organic matter in some way has a favorable effect on the formation of aggregates in the soil. It also has been observed that the beneficial influence of organic matter is more or less directly proportional to the amount and character of the organic matter applied to the soil (4, 14, 41, 45, 46, 54, 66, 84). This led to the erroneous conclusion by some that the binding of the soil particles into aggregates was due entirely to the physical effect of organic matter.

It has been noted during recent years, however, that applications of large quantities of fresh or unleached organic matter in the form of barnyard manure, crop residues, mulches, or other substances usually produced a rapid increase in the number of aggregates in soils immediately following application (79, 84). It has also been noted that the quality of the organic matter involved, as well as its quantity, is important (52). However, unless the initial application of organic matter was sufficiently large to produce a continuous supply of dissolved substances to the soil or was supplemented by additional applications at later dates this initial increase in aggregate formation soon reached a climax. Subsequently the number of aggregates in the soil underwent a steady decline.

For example, a single application of 12 tons of manure per acre to Gilpin and Halston clay loams materially increased the number of aggregates in the soil (12). In a few weeks, however, this initial rapid change in the aggregation of these soils was followed by a decline in

the number of aggregates present. It was concluded that this change, due to the addition of manure, was related in some way to the biological activity in the soil (59). It was likewise concluded that the improved physical condition of the soil probably was due to the combined transitory and stable effects of the byproducts of decomposition, and to the large amount of cells and other materials synthesized by the microorganisms.

It was observed further that organic materials which decomposed rapidly increased aggregation within a few days after they were incorporated with the soil, had their maximum effect in about 20 to 30 days, and then gradually lost their effectiveness (56). Materials that were slower in decomposing required a longer period of time to exert their binding effect but continued to be effective over a longer period. Materials that were relatively inert had little, if any effect upon aggregation. The more rapid the rate of the decomposition of the organic matter the more rapid was the rate of aggregation (48).

The concentration and nature of water-soluble binding substances in the organic materials varied depending on their sources. In some instances, very small amounts were capable of bringing about considerable aggregation. Organic amendments increased the microaggregation in the soil, even on a very light coastal plain soil which contained very little clay (43).

Decomposing organic matter conferred a good structure on the soil, and the more rapid the decomposition the better was the structure (22). The explanation of this effect is not known, but presumably some substance, which only has temporary existence in the soil, is formed as a byproduct during decomposition.

Aggregation in Gilpin silty clay loam increased with an increase in the amount of organic matter added, but the amount of change varied with the organic materials used (11). The direct increase in aggregation resulting from the addition of amounts of organic material commonly obtained from cover crops may be small. Practices which lead to increased plant growth usually increased the amount of plant residue returned to the soil (3, 49). This in turn favored a better aggregate development in the soil. The addition of sucrose was effective in the development of aggregates once it was decomposed (11, 70, 73). This was especially true with regard to the larger aggregates.

A single application of organic matter, when added to soils containing only a small amount of cementing materials necessary for the formation of stable aggregates, increased the number of large aggregates (10). On the other hand, the addition of organic matter to soils containing considerable quantities of either active inorganic or organic colloidal material did not change aggregation appreciably. The addition of sulfite liquor resulted in a considerable increase in the number of water-stable aggregates in the soil (2).

Wooster silt loam soil reached a relatively high state of aggregation under straw mulch (31). This condition was reached more quickly where unleached wheat straw and alfalfa were used than where leached materials were used. Bluegrass sod increased and maintained a high percentage of aggregates of the larger sizes but was not as effective as mulch (3, 31, 83). The value of mulch in the formation of aggregates was out of proportion to the amount of organic matter added. Mulch and sod are more effective in aggregate formation in the topsoil than in the subsoil or B-horizon. Mulch favored the formation of large aggregates (77).

Mulches produced considerable improvement in aggregation under field conditions where moderately rapid decomposition of the mulch occurred (5, 21). Aggregation under a 10-year straw mulch was much greater than that under a 5-year mulch (9).

Sucrose, unleached wheat straw, and alfalfa produced a sharp increase in aggregate formation when added to Wooster silt loam surface soil. It was concluded that the increase in aggregate formation was not due to the physical effects of the organic matter, but to soluble substances including carbohydrates. The organic matter associated with the clay fraction and presumably adsorbed on the clay particle is the fraction most effective in aggregate stabilization (74).

It has been observed that the addition of large amounts of manure to sandy soils over a period of 28 years did not bring about a high degree of aggregation. Soils to which organic matter had been added maintained a consistently greater percentage of aggregates of 0.25-mm. diameter and larger (1). That proportion of the surface soil which was free from the effects of mechanical dispersion due to rainfall, machinery, or animals; where moisture content and aeration was sufficient for maximum biological activity; where the maximum effects of alternate wetting and drying were possible; and where alternate freezing

and thawing was reduced to a minimum possessed the greatest aggregation.

Organic substances vary widely in their ability to granulate the soil, and their effectiveness in this respect depends on the state of decomposition. For example, some organic constituents, such as sugars, do not stabilize soil granules directly (53). However, once transformed into microbial tissues and decomposition products, sugars become highly effective as a soil stabilizer. Fungal filaments and certain decomposition products of bacteria, such as fats, waxes, lignins, oils, proteins, and resins, have a direct stabilizing effect (84).

MICROORGANISMS AND SOIL AGGREGATION

It has been generally assumed that the presence of inorganic colloidal materials is essential to the formation of soil crumbs and that aggregates could not be formed from pure sands and silts. During recent years the latter part of this assumption has been disproved (64). It was conclusively shown that mucus and other substances produced by soil microorganisms were effective binding agents in the formation of water-stable soil granules (26, 28, 47, 48, 49, 57, 64, 67, 70). This was true whether the soil contained a large amount of clay or consisted entirely of quartz sand (64). Substances synthesized by bacteria were found to be the most active aggregating agents (47, 62).

The organic binding forces may, for convenience, be divided into three groups. The first group is made up of colloids consisting of the decomposition products of plant residues, probably of the lyophobic and similar types (58), most of which are removed from well decomposed organic matter by treating with dilute alkali solutions.

The second group consists of cells of microorganisms and their secretory products, such as mucus, slime, or gum, produced during growth and resembling colloids and gels in their physical state. The third group consists of materials, such as polysaccharides, synthesized by certain soil microorganisms.

It was shown that there was a large increase in stickiness of cellulose (27, 57) and oat straw (78) during decomposition. An increase in percentage of water-stable aggregates was reported in soils inoculated with Azotobacter and Trichoderma (38). Straw that had been inoculated with Trichoderma lignorum and added to the soil caused a sixfold in-

crease in the number of water-stable aggregates.

A marked increase occurred in the percentage of bound materials when sand-bentonite mixtures containing sucrose or cellulose were inoculated with pure cultures of bacteria and fungi (85). Similar results were obtained using sand-clay mixtures. The binding action of the fungi was attributed to the extensive mycelium and that of Azotobacter indicum to the slimy substances produced by the organisms. Microbial groups vary widely in their ability to aggregate soil (50).

The addition to the soil of rapidly decomposable substances, such as sucrose (50, 63) and finely ground crimson clover (51, 65) resulted in a large increase in the number of bacteria and a rapid increase in water-stable aggregates. The improved aggregation persisted long after the bacterial population declined. All size-classes of organic matter used were decomposed. This indicates that some factor other than the quantity of decomposition products accounted for the greater effectiveness of the finely ground organic matter in promoting aggregation. The more rapid the decomposition of cellulosic organic matter, the greater was the production of mucus; hence the better was the resulting structure (21, 22, 36). The stability of the aggregates varied with the mucus produced by the various organisms (61). The most viscous produced the most stable aggregates. It does not necessarily follow that all viscous substances will improve soil structure (28). Lignin, proteins, oils, fats, waxes, rosin, and paraffin increased the stability of lumps of Peorian loess (51).

Aggregation in Cecil sandy loam was greatly improved through the activity of certain fungi and bacteria (62). Inoculation of nonsterile Cecil sandy loam in pots with certain cultures of bacteria and fungi, following addition to the soil of sucrose or ground oat straw, resulted in marked increases in aggregation over soil receiving similar organic-matter treatments without inoculations.

The addition of microbial decomposition products of plant material into loessial subsoil resulted in marked increase in the water stability of the soil structure (49). This increase in stability was proportional to the amount of decomposition products added.

Increased structure stability resulting from biological activity is temporary, apparently remaining only as long as the stabilizing decomposition products exist (51). Quantity of organic matter does not seem

so important as quality in producing stability. Knox topsoil, with an accumulation of decomposition products, was found to have higher stability than Peorian loess devoid of these products.

Soil organisms and their metabolic products were active in the formation and stabilization of soil structure (59, 69), although they played a greater role in the stabilization than in formation (52). The presence of living microbes was essential to the formation of aggregates in calcareous soils (35). Beneficial organisms break down plant and animal residues, liberate plant nutrients, and produce soil structural-stabilizing substances. Re-aggregation of soil is aided by the biological effects of added organic matter (6).

The addition of oat straw and especially alfalfa in the presence of molds increased aggregation (30). Inoculated soils to which neither oat straw nor alfalfa was added underwent only a slight to moderate degree of aggregation.

A species of the fungus Cladosporium, and a soil bacillus thought to belong to the Bacillus subtilis-mesentericus group, when given suitable energy source and allowed to develop in sterilized soil, brought about a very marked aggregation of the silt and clay particles of Portneuf sandy loam (47). When these organisms were grown in liquid media and the microbial cell substance was removed, the remaining material produced marked aggregation in the case of the bacillus, but only moderate aggregation in the case of the fungus. Up to 50 percent of the aggregating effect of the fungus was brought about by substances produced by the cell material, and the remainder was due to the binding influence of the fungus mycelium. The soil-bacillus cells, on the other hand, produced 20 percent of the aggregating effect, and substances produced by the cells accounted for 80 percent.

A hemicellulose-like polysaccharide synthesized by the soil bacillus was found to be primarily responsible for the marked aggregating effect. The organism synthesized a polysaccharide and brought about marked soil aggregation when supplied with organic nitrogen or when dextrose, maltose, xylose, arabinose, or sucrose was utilized as energy material. The greatest aggregation and greatest production of polysaccharide occurred with sucrose.

A variety of polysaccharides synthesized by soil bacteria brought about very marked aggregation of Delco loam soil (46). The polysac-

charides consisted of three fructosans and three dextrans containing varying amounts of uronic acid. The effectiveness of the preparations did not depend on the structural units (sugars) involved.

In general, the bacterial polysaccharides were better aggregating substances than was casein or lignin. When combined with casein and lignin, the polysaccharides, with minor exceptions, were as effective as when used alone. After the polysaccharides were incubated for 30 days, their aggregating influence had changed but slightly or had decreased. In combination with casein and lignin, they either induced little change or caused an increase in aggregation. After incubation of the sucrose-treated soil, the aggregation was considerable but was less than that resulting from any of the polysaccharides or polysaccharide, casein, or lignin treatments. Since sucrose, as such, has little influence on soil structure, the effect after incubation resulted from the production of soil-binding substances by the microorganisms decomposing it.

Levans produced by B. subtilis, growing on sucrose media, had a marked aggregating effect on soil when they contained from 0.2 to 0.3 percent nitrogen (26). However, levans with less than 0.1 percent nitrogen had little influence on aggregation. These levans may possibly have consisted of polyglucose chains connected together by units of the synthesizing enzyme which remained as an integral part of the complex micro-polysaccharide.

High aggregation is brought about largely by microbial cells, decomposition products or organic residues, and synthesized substances, some of which are polysaccharides (47, 68). These active materials, although synthesized by some microorganisms, may be slowly destroyed by others, and as a result, aggregation may decrease. It would be expected that the polysaccharides composed entirely of straight sugar-groups would undergo more or less complete decomposition, and thus their aggregating effect would be completely passive in nature. On the other hand, those containing the active uronic acid groups or those linked with nitrogenous complexes would be expected to undergo physicochemical reactions with other active substances in the soil and in some instances become resistant to further decomposition. Should such occur it is probable that only a small percentage of the total polysaccharides produced would be stabilized in this manner. However, with a continuous supply of organic material, such as occurs under sod or with heavy mulch, the cumulative total of stabilized polysaccharides

would be considerable. The bulk of soil humus consists of lignin-derived substances, nitrogenous complexes, and polysaccharides.

Polysaccharides are normal metabolic products of microorganisms. Numerous species of bacteria, fungi, and actinomycetes are capable of producing a wide variety of complex polysaccharides as cell constituents or as extracellular products (28). Hence, it is reasonable to expect that under natural conditions the diverse flora of the soil may synthesize many polysaccharides from the constituents of vegetable material, and that these substances may be of considerable importance in the formation of crumb structure in soil.

Bacterial polysaccharides of the levan and dextran types exert a pronounced binding effect on soil particles. Soil crumbs containing small amounts of levan are extraordinarily stable to the dispersing actions of water, heat, and shaking, but are eventually broken down by the activities of other microorganisms. Preliminary investigations indicate that levans are fixed on soil particles.

HUMUS AND SOIL AGGREGATION

Humus, as defined by Geltzer (23), appears to play an important role in the formation of soil aggregates. According to this definition, humus is that fraction of the organic colloids which possesses the capacity of combining with the mineral part of the soil to form organo-mineral aggregates.

More specifically, the humate fraction of the organic colloids produced in the course of the decomposition of organic matter by soil microorganisms appears to be an important factor--perhaps the most important factor--in the formation of soil aggregates (24, 25, 43, 58, 60, 72). These organic colloids, or binding agents, are distributed uniformly throughout the soil aggregates (43) and are adsorbed by soil particles (12, 37, 43, 58, 60). They are able effectively to produce stable aggregates (43), perhaps by chemical union (58), such as calcium or hydrogen bonding with inorganic colloids (25, 65). This chemical reaction is believed to take place mainly by polar adsorption, resulting from the decomposition of fresh organic matter (42, 43).

These humic substances form a protective layer at the surface of soil colloids (82) and are held at the surface of mineral gels (81). Cation exchange reactions take place in the entire protective action layer

in the vicinity of those carboxyl groups, the cations of which are capable of exchange (82).

Organic colloids, when saturated with either calcium or hydrogen ions, were several times more effective in cementing sand particles into stable aggregates than were corresponding inorganic colloid systems (52). Phenolic and alcoholic OH groups, and possibly NH_2 groups of lignin-derived material in the organic matter appeared to be important aggregating agents (60, 80). Surface active clay was necessary where polar organic substances were the aggregating agents (42).

Small aggregates are composed of particles bound by colloidal cements. The larger ones are held together by colloidal cements and by living matter such as root hairs and fungal mycelia (72). Actual structural stability is the net effect of these colloid-chemical and biological factors. A deficiency in the biological factor leads to structural breakdown into small aggregates, and a deficiency in the colloid-chemical factor leads to a more or less complete peptization.

Humic acids extracted from a number of soil groups were similar in physical and chemical properties (29). They were negatively charged hydrophilic colloids. Their acetyl and methoxyl contents were almost identical with those of lignin extracted from a prairie soil. Their base exchange was high. They possessed hydroxyl groups as well as a carboxyl group. The non-nitrogenous fraction of the humic acid consisted of a slightly modified lignin complex.

Soil colloids contain humate fractions (7, 29, 39, 40, 81, 82) which appear as two distinct fractions (7). One fraction appears as loosely bound organic matter and the other as organic matter more firmly attached to the mineral colloids (7, 68).

A glycosidic fraction was present in the uronic acid group derived from a pure polysaccharide isolated from four soils (15). The fluvic nitrogen was in part contained in nitrogenous acidic complexes and in part as simple decomposition products.

The carbon dioxide-yielding constituents in soil which are dissolved when boiled in 12 percent HCl are uronic in nature and are of microbial origin (17). Soil uronic constituents are distinctly different from those of plants and are not likely to originate directly from plants (18).

Uronic constituents of plants and soil organic matter differ not only in the rate at which their uronic units decarboxylate but also in their reaction to alkali and acetyl bromide treatment. The uronic units that are extractible from soils decarboxylate at a rate similar to that of units retained in the soil and units of the original soil, rather than like the units of plant materials and extracted plant constituents such as pectin and polyuronide hemicelluloses.

The changes in the proportion of uronic to total carbon in soil appear to be closely related to the total carbon content (19). The lower the carbon content of a given soil, the higher is the percentage of uronic carbon in the organic matter. The hypothesis that the structure-forming fraction of humus was composed of the autolytic products of bacteria was advanced (23) but many other works failed to verify it.

The form of the typical granular structure of chernozem soil is a sign of the accumulation of amorphous humus at the periphery of the aggregate (75). The appearance of amorphous humus at the periphery of the aggregate is closely related to the exchange capacity. Water-stable aggregates contain more humus, especially loosely bound humus, which is the main structure-forming agent, than ungranulated soil (68). If organic matter is firmly bound with clay as an anisotropic formation, no marked increase in the adsorption capacity occurs (75).

A supply of amorphous, or loosely bound, humus forms in the soil under the influence of manure (76). Soil organic-matter content was a good indication of soil-aggregate stability (4, 79).

Some of the humin nitrogen of muck soil apparently is derived from nonprotein material (39, 40). It was thought that the heterocyclic nitrogen of tryptophan was the source of part of the humin nitrogen (40).

Organic colloidal sols altered the viscosity of colloidal clay sols to such an extent that the change could not be explained by mechanical mixing (58). The extent of the alteration in viscosity was influenced by the quality of organic colloid added, the cation present, and the type of soil colloid used.

To form active humus under sod, the slow fungal process by which aerobic decomposition usually starts must be quickly replaced by the more active bacterial processes (22). The bacterial microflora of the surface layer of soil is the most significant factor in the formation of

active humus under permanent grasses (20). Surface soil bacteria of the Pseudomonas type assists in the formation of exceptionally stable soil structure under these conditions.

SUMMARY

A review and analysis are presented of the most important literature dealing with the method of soil aggregate formation. It is shown that under some conditions clay may act directly as a binding agent in forming aggregates. However, most of the data presented indicate that aggregate formation in soils is associated with adequate supplies of biologically active organic matter and that substances produced or synthesized by microorganisms play an active part. More specifically, the humate fraction of the organic colloids produced in the course of decomposition of organic matter by soil microorganisms appears to be one of the main--if not the chief--factors contributing to the formation of soil aggregates. They presumably are negatively charged hydrophylic colloids and are distributed uniformly through the soil aggregates. These substances are adsorbed to colloidal clay particles, perhaps by electrochemical union with inorganic colloids. Apparently they are bound through the carbon linkage "bridge" between reactive groups on the polymer. The presence of small amounts of sodium, calcium, magnesium, and other cations increases the aggregating effect with low concentrations of humate fractions.

Locked to the soil particles, the humate fraction or hydrophylic colloids act like bridges between them, keeping them from separating yet at the same time holding them at arms length so they won't pack down tight.

Since certain other groups of soil microorganisms break down these organic colloids as they are formed, it is necessary to maintain a continuous supply of fresh organic matter in the soil if a high state of aggregation is to continue. This can be accomplished by using sod cover or mulches to which fresh materials are added frequently.

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